EXHIBIT J

Designation: D 790 – 96a

An American National Standard

Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials[1]

This standard is issued under the fixed designation D 790; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This test method has been approved for use by agencies of the Department of Defense to replace Method 1031 of Federal Test Method Standard 406. Consult the DoD Index of Specifications and Standards for the specific year of issue which has been adopted by the Department of Defense.

1. Scope

1.1 These test methods cover the determination of flexural properties of unreinforced and reinforced plastics, including high-modulus composites and electrical insulating materials in the form of rectangular bars molded directly or cut from sheets, plates, or molded shapes. These test methods are generally applicable to rigid and semirigid materials. However, flexural strength cannot be determined for those materials that do not break or that do not fail in the outer fibers. Two test methods are described as follows:

1.1.1 *Test Method I*—A three-point loading system utilizing center loading on a simply supported beam.

1.1.2 *Test Method II*—A four-point loading system utilizing two load points equally spaced from their adjacent support points, with a distance between load points of either one third or one half of the support span.

1.2 Either test method can be used with the two procedures that follow:

1.2.1 *Procedure A*, designed principally for materials that break at comparatively small deflections.

1.2.2 *Procedure B*, designed particularly for those materials that undergo large deflections during testing.

1.2.3 Procedure A shall be used for measurement of flexural properties, particularly flexural modulus, unless the material specification states otherwise. Procedure B may be used for measurement of flexural strength.

1.3 Comparative tests may be run according to either test method or procedure, provided that the test method or procedure is found satisfactory for the material being tested.

1.4 The values stated in SI units are to be regarded as the standard. The values provided in parentheses are for information only.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

D 618 Practice for Conditioning Plastics and Electrical Insulating Materials for Testing[2]

D 638 Test Method for Tensile Properties of Plastics[2]

D 883 Terminology Relating to Plastics[2]

D 4000 Classification System for Specifying Plastic Materials[3]

D 4066 Specification for Nylon Injection and Extrusion Materials[3]

E 4 Practices for Force Verification of Testing Machines[4]

E 691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method[5]

3. Terminology

3.1 *Definitions*—Definitions of terms applying to these test methods appear in Terminology D 883 and Annex A1 of Test Method D 638.

4. Summary of Test Methods

4.1 A bar of rectangular cross section is tested in flexure as a beam as follows:

4.1.1 *Test Method I*—The bar rests on two supports and is loaded by means of a loading nose midway between the supports (see Fig. 1).

4.1.2 *Test Method II*—The bar rests on two supports and is loaded at two points (by means of two loading noses), each an equal distance from the adjacent support point. The distance between the loading noses (that is, the load span) is either one third or one half of the support span (see Fig. 2).

4.2 The specimen is deflected until rupture occurs in the outer fibers or until the maximum fiber strain (see 12.9) of 5 % is reached, whichever occurs first.

5. Significance and Use

5.1 Flexural properties determined by Test Method I are especially useful for quality control and specification purposes.

5.2 For many materials, there may be a specification that requires the use of these test methods, but with some procedural modifications that take precedence when adhering to the specification. It is therefore advisable to refer to that material specification before using these test methods.

[1] These test methods are under the jurisdiction of ASTM Committee D-20 on Plastics and are the direct responsibility of Subcommittee D20.10 on Mechanical Properties.

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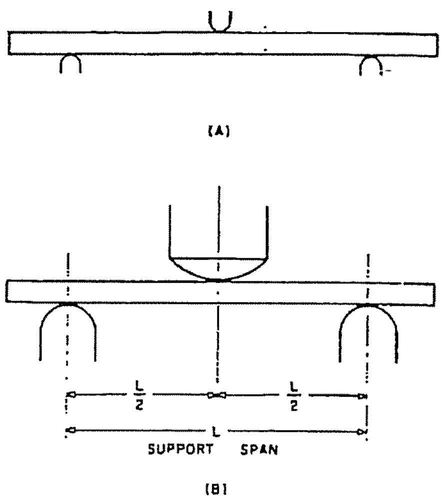
The following changes were made to this edition of these test methods: Section 2.11.3 was revised.

[2] *Annual Book of ASTM Standards*, Vol 08.01.

[3] *Annual Book of ASTM Standards*, Vol 08.02.

[4] *Annual Book of ASTM Standards*, Vol 03.01.

[5] *Annual Book of ASTM Standards*, Vol 14.02.



NOTE—(*a*) Minimum radius = 3.2 mm (⅛ in.). (*b*) Maximum radius supports = 1.6 times specimen depth; maximum radius loading nose = 4 times specimen depth.

FIG. 1 Allowable Range of Loading Nose and Support Radii

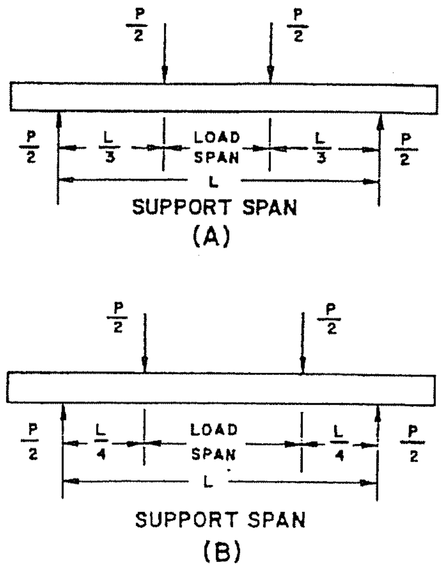
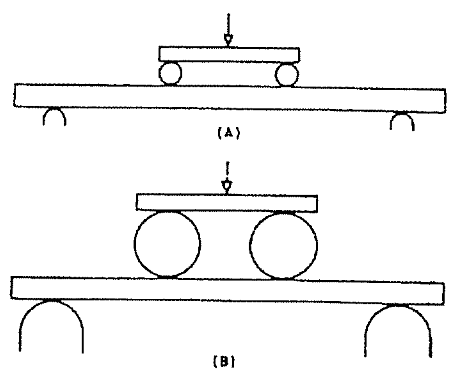


FIG. 2 Loading Diagram

Table 1 in Classification D 4000 lists the ASTM materials standards that currently exist.

5.3 Materials that do not fail at the point of maximum stress under Test Method I should be tested by Test Method II. Flexural properties determined by Test Method II are also useful for quality control and specification purposes. The basic difference between the two test methods is in the location of the maximum bending moment and maximum axial fiber stresses. The maximum axial fiber stresses occur on a line under the loading nose in Test Method I and over the area between the loading noses in Test Method II.

5.4 Flexural properties may vary with specimen depth, temperature, atmospheric conditions, and the difference in rate of straining specified in Procedures A and B (see also Note 7).



NOTE—(*a*) Minimum radius = 3.2 mm (⅛ in.). (*b*) Maximum radius = 1.6 times specimen depth.

FIG. 3 Allowable Range of Loading Nose and Support Radii

6. Apparatus

6.1 *Testing Machine*—A properly calibrated testing machine that can be operated at constant rates of crosshead motion over the range indicated, and in which the error in the load measuring system shall not exceed ±1 % of maximum load expected to be measured. It shall be equipped with a deflection measuring device. The stiffness of the testing machine shall be such that the total elastic deformation of the system does not exceed 1 % of the total deflection of the test specimen during testing, or appropriate corrections shall be made. The load indicating mechanism shall be essentially free from inertial lag at the crosshead rate used. The accuracy of the testing machine shall be verified in accordance with Practices E 4.

6.2 *Loading Noses and Supports*—The loading nose or noses and supports shall have cylindrical surfaces. In order to avoid excessive indentation, or failure due to stress concentration directly under the loading nose or noses, the radii of the loading nose and supports shall be 5.0 ± 0.1 mm (0.197 ± 0.004 in.) unless otherwise specified or agreed upon between the interested parties. When other loading nose or noses and supports are used they must comply with the following requirements: (*1*) they shall be at least 3.2 mm (⅛ in.) for all specimens, and (*2*) for specimens 3.2 mm (⅛ in.) or greater in depth, the radius of the supports may be up to 1.6 times the specimen depth. They shall be this large if significant indentation or compressive failure occurs. The arc of the loading nose in contact with the specimen shall be sufficiently large to prevent contact of the specimen with the sides of the nose or noses (see Fig. 1 for Test Method I and Fig. 3 for Test Method II).

NOTE 1—Test data have shown that the loading nose and support dimensions can influence the flexural modulus and flexural strength values. The loading nose dimension has the greater influence. Dimensions of loading nose and supports must be specified for material specifications.

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7. Test Specimens

7.1 The specimens may be cut from sheets, plates, or

TABLE 1 Recommended Dimensions for Test Specimens of Sections 7.3 and 7.5 for Various Support Span-to-Depth Ratios (See Note 6)
Test Method I (3-Point Loading)

		Support Span-to-Depth Ratio (See Note 6)											
		L/d = 16 to 1			L/d = 32 to 1			L/d = 40 to 1			L/d = 60 to 1		
Nominal Specimen Depth, mm (in.)	Specimen Width, mm (in.)	Specimen Length, mm (in.)	Support Span, mm (in.)	Rate of Cross-head Motion (Procedure A), mm (in.)/min[A]	Specimen Length, mm (in.)	Support Span, mm (in.)	Rate of Cross-head Motion (Procedure A), mm (in.)/min[A]	Specimen Length, mm (in.)	Support Span, mm (in.)	Rate of Cross-head Motion (Procedure A), mm (in.)/min[A]	Specimen Length, mm (in.)	Support Span, mm (in.)	Rate of Cross-head Motion (Procedure A), mm (in.)/min[A]
0.8 (1/32)	25 (1)	50 (2)	16 (5/8)[B]	0.5 (0.02)	50 (2)	25 (1)	1.3 (0.05)	60 (2 1/4)	30 (1 1/4)	2.0 (0.08)	60 (2 3/8)	48 (1 7/8)	4.8 (0.19)
1.6 (1/16)	25 (1)	50 (2)	25 (1)	0.8 (0.03)	80 (3)	50 (2)	2.8 (0.11)	90 (3 1/2)	60 (2 1/2)	4.3 (0.17)	124 (4 7/8)	95 (3 3/4)	9.4 (0.37)
2.4 (3/32)	25 (1)	60 (2 1/2)	40 (1 1/2)	1.0 (0.04)	100 (4)	80 (3)	4.1 (0.16)	120 (4 3/4)	95 (3 3/4)	6.4 (0.25)	185 (7 9/32)	143 (5 5/8)	14.2 (0.56)
3.2 (1/8)	25 (1)	80 (3)	50 (2)	1.3 (0.05)	130 (5)	100 (4)	5.3 (0.21)	180 (7)	130 (5)	8.4 (0.33)	247 (9 3/4)	190 (7 1/2)	18.8 (0.74)
4.8 (3/16)	13 (1/2)	100 (4)	80 (3)	2.0 (0.08)	191 (7 1/2)	150 (6)	8.1 (0.32)	240 (9 1/2)	191 (7 1/2)	12.7 (0.50)	372 (14 5/8)	286 (11 1/4)	28.4 (1.12)
6.4 (1/4)	13 (1/2)	130 (5)	100 (4)	2.8 (0.11)	250 (10)	200 (8)	10.9 (0.43)	330 (13)	250 (10)	17.0 (0.67)	495 (19 1/2)	381 (15)	37.8 (1.49)
9.6 (3/8)	13 (1/2)	191 (7 1/2)	150 (6)	4.1 (0.16)	380 (15)	300 (12)	16.3 (0.64)	480 (19)	380 (15)	25.4 (1.00)	744 (29 5/16)	572 (22 1/2)	56.8 (2.24)
12.7 (1/2)	13 (1/2)	250 (10)	200 (8)	5.3 (0.21)	495 (19 1/2)	410 (16)	21.6 (0.85)	640 (25)	510 (20)	34.0 (1.34)	991 (39)	762 (30)	76.2 (3.00)
19.1 (3/4)	19 (3/4)	380 (15)	300 (12)	8.1 (0.32)	740 (29)	610 (24)	32.5 (1.28)	940 (37)	760 (30)	50.8 (2.00)	1486 (58 1/2)	1143 (45)	114 (4.49)
25.4 (1)	25 (1)	495 (19 1/2)	410 (16)	10.9 (0.43)	990 (39)	810 (32)	43.4 (1.71)	1240 (49)	1020 (40)	67.8 (2.67)	1981 (78)	1524 (60)	152 (5.98)

[A] Rates indicated are for Procedure A, where strain rate is 0.01 mm/mm/min (0.01 in./in./min). To obtain rates for Procedure B, where strain rate is 0.10 mm/mm/min (0.10 in./in./min), multiply these values by 10. Procedure A is to be used for all specification purposes unless otherwise stated in the specifications. See 10.1.3 for the method of calculation.

[B] This support span-to-depth ratio is greater than 16 to 1 in order to give clearance between moving head and specimen support.

molded shapes, or may be molded to the desired finished dimensions.

NOTE 2—Any necessary polishing of specimens shall be done only in the lengthwise direction of the specimen.

7.2 *Sheet Materials* (except laminated thermosetting materials and certain materials used for electrical insulation, including vulcanized fiber and glass bonded mica):

7.2.1 *Materials 1.6 mm (1/16 in.) or Greater in Thickness*—For flatwise tests, the depth of the specimen shall be the thickness of the material. For edgewise tests, the width of the specimen shall be the thickness of the sheet, and the depth shall not exceed the width (see Notes 3 and 4). For all tests, the support span shall be 16 (tolerance +4 or −2) times the depth of the beam. Specimen width shall not exceed one fourth of the support span for specimens greater than 3.2 mm (1/8 in.) in depth. Specimens 3.2 mm or less in depth shall be 12.7 mm (1/2 in.) in width. The specimen shall be long enough to allow for overhanging on each end of at least 10 % of the support span, but in no case less than 6.4 mm (1/4 in.) on each end. Overhang shall be sufficient to prevent the specimen from slipping through the supports.

NOTE 3—Whenever possible, the original surface of the sheet shall be unaltered. However, where testing machine limitations make it impossible to follow the above criterion on the unaltered sheet, one or both surfaces shall be machined to provide the desired dimensions, and the location of the specimens with reference to the total depth shall be noted. The value obtained on specimens with machined surfaces may differ from those obtained on specimens with original surfaces. Consequently, any specifications for flexural properties on the thicker sheets must state whether the original surfaces are to be retained or not. When only one surface was machined, it must be stated whether the machined surface was on the tension or compression side of the beam.

NOTE 4—Edgewise tests are not applicable for sheets that are so thin that specimens meeting these requirements cannot be cut. If specimen depth exceeds the width, buckling may occur.

7.2.2 *Materials Less than 1.6 mm (1/16 in.) in Thickness*—The specimen shall be 50.8 mm (2 in.) long by 12.7 mm (1/2 in.) wide, tested flatwise on a 25.4-mm (1-in.) support span.

NOTE 5—Use of the formulas for simple beams cited in these test methods for calculating results presumes that beam width is small in comparison with the support span. Therefore, the formulas do not apply rigorously to these dimensions.

NOTE 6—Where machine sensitivity is such that specimens of these dimensions cannot be measured, wider specimens or shorter support spans, or both, may be used, provided the support span-to-depth ratio is at least 14 to 1. All dimensions must be stated in the report (see also Note 5).

7.3 *Laminated Thermosetting Materials and Sheet and Plate Materials Used for Electrical Insulation, Including Vulcanized Fiber and Glass-Bonded Mica*—Test the specimens in accordance with Table 1 for Test Method I and either Table 2 or 3 for Test Method II. For paper-base and fabric-base grades over 25.4 mm (1 in.) in nominal thickness, the specimens shall be machined on both surfaces to a depth of 25.4 mm. For glass-base and nylon-base grades, specimens over 12.7 mm (1/2 in.) in nominal depth shall be machined on both surfaces to a depth of 12.7 mm. The support span-to-depth ratio shall be chosen such that failures occur in the outer fibers of the specimens, due only to the bending moment (Note 7). Three recommended support span-to-depth ratios are 16, 32, and 40 to 1. When laminated materials exhibit low compressive strength perpendicular to the laminations, they shall be loaded with a large radius loading nose (up to 4 times the specimen depth for Test Method I and 1.5 times the specimen depth for Test Method II) to prevent premature damage to the outer fibers.

7.4 *Molding Materials (Thermoplastics and Thermosets)*—The recommended specimen for molding materials is 127 by 12.7 by 3.2 mm (5 by 1/2 by 1/8 in.) tested flatwise on a support span, resulting in a support span-to-depth ratio of 16 (tolerance +4 or −2). Thicker specimens should be avoided if they exhibit significant shrink marks or bubbles when molded.

7.5 *High-Strength Reinforced Composites, Including Highly Orthotropic Laminates*—Specimens shall be tested in accordance with Table 1 for Test Method I and either Table 2 or 3 for Test Method II. The support span-to-depth ratio

TABLE 2 Recommended Dimensions for Test Specimens of Sections 7.3 and 7.5 for Various Support Span-to-Depth Ratios (See Note 6)
Test Method II [4-Point Loading at 1/3 Points, Fig. 2(A)]

Nominal Specimen Depth, mm (in.)	Specimen Width, mm (in.)	Specimen Length, mm (in.)	Support Span, mm (in.)	Load Span, mm (in.)	Rate of Crosshead Motion (Procedure A), mm (in.)/min[A]
		L/d = 16 to 1			
1.6 (1/16)	25 (1)	51 (2)	25 (1)	8.4 (0.33)	0.7 (0.03)
2.4 (3/32)	25 (1)	64 (2½)	38 (1½)	12.7 (0.50)	1.1 (0.04)
3.2 (1/8)	25 (1)	76 (3)	51 (2)	17.0 (0.67)	1.5 (0.06)
4.8 (3/16)	13 (½)	102 (4)	76 (3)	25.4 (1.00)	2.2 (0.09)
6.4 (¼)	13 (½)	127 (5)	102 (4)	33.8 (1.33)	3.0 (0.11)
9.6 (3/8)	13 (½)	190 (7½)	152 (6)	50.8 (2.00)	4.5 (0.18)
12.7 (½)	13 (½)	254 (10)	203 (8)	67.8 (2.67)	6.0 (0.24)
19.1 (¾)	19 (¾)	381 (15)	305 (12)	102 (4.00)	9.0 (0.35)
25.4 (1)	25 (1)	495 (19½)	406 (16)	135 (5.33)	12.0 (0.48)
		L/d = 32 to 1			
1.6 (1/16)	25 (1)	76 (3)	51 (2)	17.0 (0.67)	3.0 (0.11)
2.4 (3/32)	25 (1)	102 (4)	76 (3)	25.4 (1.00)	4.5 (0.18)
3.2 (1/8)	25 (1)	127 (5)	102 (4)	33.8 (1.33)	6.0 (0.24)
4.8 (3/16)	13 (½)	190 (7½)	165 (6½)	55.1 (2.17)	10.5 (0.41)
6.4 (¼)	13 (½)	254 (10)	203 (8)	67.8 (2.67)	11.9 (0.48)
9.6 (3/8)	13 (½)	381 (15)	305 (12)	102 (4)	17.9 (0.71)
12.7 (½)	13 (½)	495 (19½)	406 (16)	135 (5.3)	24.1 (0.95)
19.1 (¾)	19 (¾)	737 (29)	610 (24)	204 (8.0)	36.0 (1.42)
25.4 (1)	25 (1)	991 (39)	813 (32)	271 (10.7)	48.1 (1.89)
		L/d = 40 to 1			
1.6 (1/16)	25 (1)	89 (3½)	63 (2½)	21.2 (0.83)	4.6 (0.19)
2.4 (3/32)	25 (1)	121 (4¾)	95 (3¾)	31.8 (1.25)	7.0 (0.27)
3.2 (1/8)	25 (1)	178 (7)	127 (5)	42.4 (1.67)	9.3 (0.37)
4.8 (3/16)	13 (½)	241 (9½)	190 (7½)	63.5 (2.50)	13.9 (0.56)
6.4 (¼)	13 (½)	330 (13)	254 (10)	84.6 (3.33)	18.7 (0.74)
9.6 (3/8)	13 (½)	483 (19)	381 (15)	127 (5.0)	28.0 (1.11)
12.7 (½)	13 (½)	635 (25)	508 (20)	169 (6.7)	37.6 (1.48)
19.1 (¾)	19 (¾)	940 (37)	762 (30)	254 (10.0)	56.2 (2.22)
25.4 (1)	25 (1)	1245 (49)	1016 (40)	338 (13.3)	75.1 (2.96)
		L/d = 60 to 1			
1.6 (1/16)	25 (1)	124 (4 7/8)	95 (3¾)	31.7 (1¼)	10.4 (0.41)
2.4 (3/32)	25 (1)	185 (7 9/32)	143 (5 5/8)	47.6 (1 7/8)	15.8 (0.62)
3.2 (1/8)	25 (1)	247 (9¾)	190 (7½)	63.3 (2½)	20.9 (0.82)
4.8 (3/16)	13 (½)	372 (14 5/8)	286 (11¼)	95.3 (3¾)	31.5 (1.24)
6.4 (¼)	13 (½)	495 (19½)	381 (15)	127 (5)	41.9 (1.65)
9.6 (3/8)	13 (½)	744 (29 5/16)	572 (22½)	191 (7½)	63.1 (2.48)
12.7 (½)	13 (½)	991 (39)	762 (30)	254 (10)	84.6 (3.33)
19.1 (¾)	19 (¾)	1486 (58½)	1143 (45)	381 (15)	127 (5.00)
25.4 (1)	25 (1)	1981 (78)	1524 (60)	508 (20)	169 (6.66)

[A] Rates indicated are for Procedure A, where strain rate is 0.01 mm/mm·min (0.01 in./in.·min). To obtain rates for Procedure B, where strain rate is 0.10 mm/mm·min (0.10 in./in.·min), multiply these values by 10. Procedure A is to be used for all specification purposes, unless otherwise stated in the specifications. See 10.2.3 for the method of calculation.

shall be chosen such that failures occur in the outer fibers of the specimens, due only to the bending moment (Note 7). Three recommended support span-to-depth ratios are 16:1, 32:1, and 40:1. However, for some highly anisotropic composites, shear deformation can significantly influence modulus measurements, even at span-to-depth ratios as high as 40:1. Hence, for these materials, an increase in span-to-depth ratio to 60:1 is recommended to eliminate shear effects when modulus data are required. It should also be noted that the flexural modulus of highly anisotropic laminates is a strong function of ply-stacking sequence and will not necessarily correlate with tensile modulus, which is not stacking-sequence dependent.

NOTE 7—As a general rule, support span-to-depth ratios of 16 are satisfactory when the ratio of the tensile strength to shear strength is less than 8 to 1, but the support span-to-depth ratio must be increased for composite laminates having relatively low shear strength in the plane of the laminate and relatively high tensile strength parallel to the support span.

8. Number of Test Specimens

8.1 At least five specimens shall be tested for each sample in the case of isotropic materials or molded specimens.

8.2 For each sample of anisotropic material in sheet form, at least five specimens shall be tested for each of the following conditions. Recommended conditions are flatwise and edgewise tests on specimens cut in lengthwise and crosswise directions of the sheet. For the purposes of this test, "lengthwise" shall designate the principal axis of anisotropy and shall be interpreted to mean the direction of the sheet known to be stronger in flexure. "Crosswise" shall be the sheet direction known to be the weaker in flexure and shall be at 90° to the lengthwise direction.

TABLE 3 Recommended Dimensions for Test Specimens of Sections 7.3 and 7.5 for Various Support Span-to-Depth Ratios (See Note 7) Test Method II [4-Point Loading at ¼ Points, Fig. 2(B)]

Nominal Specimen Depth, mm (in.)	Specimen Width, mm (in.)	Specimen Length, mm (in.)	Support Span, mm (in.)	Load Span, mm (in.)	Rate of Crosshead Motion (Procedure A), mm (in.)/min[A]
		L/d = 16 to 1			
1.6 (1/16)	25 (1)	51 (2)	25 (1)	12.5 (0.50)	0.8 (0.03)
2.4 (3/32)	25 (1)	64 (2½)	38 (1½)	19.0 (0.75)	1.0 (0.04)
3.2 (1/8)	25 (1)	76 (3)	51 (2)	25.5 (1)	1.3 (0.05)
4.8 (3/16)	13 (½)	102 (4)	76 (3)	38 (1.50)	2.0 (0.08)
6.4 (¼)	13 (½)	127 (5)	102 (4)	51 (2)	2.8 (0.11)
9.6 (3/8)	13 (½)	190 (7½)	152 (6)	76 (3)	4.1 (0.16)
12.7 (½)	13 (½)	254 (10)	203 (8)	102 (4)	5.3 (0.21)
19.1 (¾)	19 (¾)	381 (15)	305 (12)	153 (6)	8.1 (0.32)
25.4 (1)	25 (1)	495 (19½)	406 (16)	203 (8)	10.9 (0.43)
		L/d = 32 to 1			
1.6 (1/16)	25 (1)	76 (3)	51 (2)	25.5 (1)	2.8 (0.11)
2.4 (3/32)	25 (1)	102 (4)	76 (3)	38 (1.50)	4.1 (0.16)
3.2 (1/8)	25 (1)	127 (5)	102 (4)	51 (2)	5.3 (0.21)
4.8 (3/16)	13 (½)	190 (7½)	165 (6½)	82.5 (3.25)	8.1 (0.32)
6.4 (¼)	13 (½)	254 (10)	203 (8)	102 (4)	10.9 (0.43)
9.6 (3/8)	13 (½)	381 (15)	305 (12)	153 (6)	16.3 (0.64)
12.7 (½)	13 (½)	495 (19½)	406 (16)	203 (8)	21.6 (0.85)
19.1 (¾)	19 (¾)	737 (29)	610 (24)	305 (12)	32.5 (1.28)
25.4 (1)	25 (1)	991 (39)	813 (32)	407 (16)	43.4 (1.71)
		L/d = 40 to 1			
1.6 (1/16)	25 (1)	89 (3½)	63 (2½)	31.5 (1.25)	4.3 (0.17)
2.4 (3/32)	25 (1)	121 (4¾)	95 (3¾)	47.5 (1.88)	6.4 (0.25)
3.2 (1/8)	25 (1)	178 (7)	127 (5)	63.5 (2.50)	8.4 (0.33)
4.8 (3/16)	13 (½)	241 (9⅞)	190 (7½)	95.0 (3.75)	12.7 (0.50)
6.4 (¼)	13 (½)	330 (13)	254 (10)	127 (5.0)	17.0 (0.67)
9.6 (3/8)	13 (½)	483 (19)	381 (15)	191 (7.5)	25.4 (1.00)
12.7 (½)	13 (½)	635 (25)	508 (20)	254 (10.0)	34.0 (1.34)
19.1 (¾)	19 (¾)	940 (37)	762 (30)	381 (15.0)	50.8 (2.00)
25.4 (1)	25 (1)	1245 (49)	1016 (40)	508 (20.0)	67.8 (2.67)
		L/d = 60 to 1			
1.6 (1/16)	25 (1)	124 (4⅞)	95 (3¾)	47.5 (1⅞)	9.4 (0.37)
2.4 (3/32)	25 (1)	185 (7 9/32)	143 (5⅝)	71.5 (2 13/16)	14.2 (0.56)
3.2 (1/8)	25 (1)	247 (9¾)	190 (7½)	95.0 (3¾)	18.8 (0.74)
4.8 (3/16)	13 (½)	372 (14⅝)	286 (11¼)	143 (5⅝)	28.4 (1.12)
6.4 (¼)	13 (½)	495 (19½)	381 (15)	191 (7½)	37.8 (1.49)
9.6 (3/8)	13 (½)	744 (29 5/16)	572 (22½)	286 (11¼)	56.8 (2.24)
12.7 (½)	13 (½)	991 (39)	762 (30)	381 (15)	76.2 (3.00)
19.1 (¾)	19 (¾)	1486 (58½)	1143 (45)	572 (22.5)	114 (4.49)
25.4 (1)	25 (1)	1981 (78)	1524 (60)	762 (30)	152 (5.98)

[A] Rates indicated are for Procedure A, where strain rate is 0.01 mm/mm·min (0.01 in./in.·min). To obtain rates for Procedure B, where strain rate is 0.10 mm/mm·min (0.10 in./in.·min), multiply these values by 10. Procedure A is to be used for all specification purposes, unless otherwise stated in the specifications. See 10.2.3 for the method of calculation.

9. Conditioning

9.1 *Conditioning*—Condition the test specimens at 23 ± 2°C (73.4 ± 3.6°F) and 50 ± 5 % relative humidity for not less than 40 h prior to testing in accordance with Procedure A of Practice D 618 for those tests where conditioning is required. In cases of disagreement, the tolerances shall be ±1°C (±1.8°F) and ±2 % relative humidity.

9.1.1 Note that for some hygroscopic materials, such as nylons, the material specifications (for example, Specification D 4066) call for testing "dry as-molded specimens." Such requirements take precedence over the above routine preconditioning to 50 % relative humidity and require sealing the specimens in water vapor-impermeable containers as soon as molded and not removing them until ready for testing.

9.2 *Test Conditions*—Conduct tests in the standard laboratory atmosphere of 23 ± 2°C (73.4 ± 3.6°F) and 50 ± 5 % relative humidity, unless otherwise specified in the test methods or in this specification. In cases of disagreement, the tolerances shall be ±1°C (±1.8°F) and ±2 % relative humidity.

10. Procedure

10.1 *Test Method I—Procedure A:*

10.1.1 Use an untested specimen for each measurement. Measure the width and depth of the specimen to the nearest 0.03 mm (0.001 in.) at the center of the support span. For specimens less than 2.54 mm (0.100 in.) in depth, measure the depth to the nearest 0.003 mm (0.0001 in.).

10.1.2 Determine the support span to be used as described in Section 7 and set the support span to within 1 % of the determined value.

10.1.3 Measure the span accurately to the nearest 0.1 mm (0.004 in.) for spans less than 63 mm (2.5 in.) and to the nearest 0.3 mm (0.012 in.) for spans greater than or equal to 63 mm (2.5 in.). Use the measured span for all calculations.

See Annex A2 for information on the determination of and setting of the span.

10.1.4 If Table 1 is used, set the machine to the specified rate of crosshead motion, or as near as possible to it. If Table 1 is not used, calculate the rate of crosshead motion as follows and set the machine for the calculated rate, or as near as possible to it:

$$R = ZL^2/6d \quad (1)$$

where:

R = rate of crosshead motion, mm (in.)/min,
L = support span, mm (in.),
d = depth of beam, mm (in.), and
Z = rate of straining of the outer fiber, mm/mm·min (in./in.·min). Z shall equal 0.01.

In no case shall the actual crosshead rate differ from that specified by Table 1, or that calculated from Eq 1, by more than ±50 %.

10.1.5 Align the loading nose and supports so that the axes of the cylindrical surfaces are parallel and the loading nose is midway between the supports. The parallelism may be checked by means of a plate with parallel grooves into which the loading nose and supports will fit when properly aligned. Center the specimen on the supports, with the long axis of the specimen perpendicular to the loading nose and supports.

10.1.6 Apply the load to the specimen at the specified crosshead rate, and take simultaneous load-deflection data. Measure deflection either by a gage under the specimen in contact with it at the center of the support span, the gage being mounted stationary relative to the specimen supports, or by measurement of the motion of the loading nose relative to the supports. In either case, make appropriate corrections for indentation in the specimens and deflections in the weighing system of the machine. Load-deflection curves may be plotted to determine the flexural yield strength, secant or tangent modulus of elasticity, and the total work measured by the area under the load-deflection curve.

10.1.7 Terminate the test if the maximum strain in the outer fibers has reached 0.05 mm/mm (in./in.) (Notes 8 and 9). The deflection at which this strain occurs may be calculated by letting r equal 0.05 mm/mm (in./in.) as follows:

$$D = rL^2/6d \quad (2)$$

5.3%

where:

D = midspan deflection, mm (in.),
r = strain, mm/mm (in./in.),
L = support span, mm (in.), and
d = depth of beam, mm (in.).

NOTE 8—For some materials the increase in strain rate provided under Procedure B may induce the specimen to yield or rupture, or both, within the required 5 % strain limit.

NOTE 9—Beyond 5 % strain, these test methods are not applicable, and some other property might be measured (for example, Test Method D 638 may be considered).

10.2 *Test Method II—Procedure A:*

10.2.1 See 10.1.1.

10.2.2 See 10.1.2.

10.2.3 If Table 2 or 3 is used, set the machine as close as possible to the specified rate of crosshead motion. If Table 2 or 3 is not used, calculate the rate of crosshead motion as follows, and set the machine as near as possible to that calculated rate for a load span of one third of the support span:

$$R = 0.185ZL^2/d \quad (3a)$$

For a load span of one half of the support span:

$$R = 0.167ZL^2/d \quad (3b)$$

where:

R = rate of crosshead motion, mm (in.)/min,
L = support span, mm (in.),
d = depth of beam, mm (in.), and
Z = rate of straining of the outer fibers, mm/mm (in./in.)·min. Z shall equal 0.01.

In no case shall the actual crosshead rate differ from that specified by Table 2 or 3, or that calculated from Eq 3a or 3b, by more than ±50 %.

10.2.4 Align the loading noses and supports so that the axes of the cylindrical surfaces are parallel and the load span is either one third or one half of the support span. This parallelism may be checked by means of a plate containing parallel grooves into which the loading noses and supports will fit when properly aligned. Center the specimen on the supports, with the long axis of the specimen perpendicular to the loading noses and supports. The loading nose assembly shall be of the type which will not rotate.

10.2.5 Apply the load to the specimen at the specified crosshead rate, and take simultaneous load-deflection data. Measure deflection by a gage under the specimen in contact with it at the common center of the spans, the gage being mounted stationary relative to the specimen supports. Make appropriate corrections for indentation in the specimens and deflections in the weighing system of the machine. Load-deflection curves may be plotted to determine the flexural yield strength, secant or tangent modulus of elasticity, and the total work measured by the area under the load-deflection curve.

10.2.6 If no break has occurred in a specimen by the time the maximum strain in the outer fibers has reached 0.05 mm/mm (in./in.), discontinue the test (Notes 8 and 9). The deflection at which this strain occurs may be calculated by letting r equal 0.05 mm/mm (in./in.) as follows for a load span of one third of the support span:

$$D = 0.21rL^2/d \quad (4a)$$

For a load span of one half of the support span:

$$D = 0.23rL^2/d \quad (4b)$$

where:

D = midspan deflection, mm (in.),
r = strain, mm/mm (in./in.),
L = support span, mm (in.), and
d = depth of beam, mm (in.).

Ratio .533

10.3 *Test Methods I and II, Procedure B:*

10.3.1 Use an untested specimen for each measurement.

10.3.2 Test conditions shall be identical to those described in 10.1 or 10.2, except that the rate of straining of the outer fibers shall be 0.10 mm/mm (in./in.)/min.

10.3.3 If no break has occurred in the specimen by the time the maximum strain in the outer fibers has reached 0.05 mm/mm (in./in.), discontinue the test (Note 9).

11. Retests

11.1 Values for properties at rupture shall not be calculated for any specimen that breaks at some obvious, fortuitous flaw, unless such flaws constitute a variable being studied. Retests shall be made for any specimen on which values are not calculated.

12. Calculation

NOTE 10—In determination of the calculated value of some of the properties listed in this section it is necessary to determine if the toe compensation (see Annex A1) adjustment must be made. This toe compensation correction shall be made only when it has been shown that the toe region of the curve is due to the takeup of slack, alignment, or seating of the specimen and not a material response. To determine the degree to which this toe region is due to takeup of slack, a steel bar can be used in place of a specimen. The measurement should be made only at the loads, which would be typical of the material under test.

12.1 *Maximum Fiber Stress, Test Method I*—When a beam of homogeneous, elastic material is tested in flexure as a simple beam supported at two points and loaded at the midpoint, the maximum stress in the outer fibers occurs at midspan. This stress may be calculated for any point on the load-deflection curve by the following equation (Notes 11 and 12):

$$S = 3PL/2bd^2 \tag{5}$$

where:
S = stress in the outer fibers at midspan, MPa (psi),
P = load at a given point on the load-deflection curve, N (lbf),
L = support span, mm (in.),
b = width of beam tested, mm (in.), and
d = depth of beam tested, mm (in.).

NOTE 11—Equation 5 applies strictly to materials for which the stress is linearly proportional to strain up to the point of rupture and for which the strains are small. Since this is not always the case, a slight error will be introduced in the use of this equation. The equation will, however, be valid for comparison data and specification values up to the maximum fiber strain of 5 % for specimens tested by the procedure herein described. It should be noted that the maximum stress may not occur in the outer fibers for a highly orthotropic laminate.[6] Laminated beam theory must be applied to determine the maximum tensile stress at failure. Thus, Eq 5 yields an apparent strength based on homogeneous beam theory. This apparent strength is highly dependent on the ply-stacking sequence for highly orthotropic laminates.

NOTE 12—The above calculation is not valid if the specimen is slipping excessively between the supports.

12.2 *Maximum Fiber Stress for Beams Tested at Large Support Spans, Test Method I*—If support span-to-depth ratios greater than 16 to 1 are used such that deflections in excess of 10 % of the support span occur, the maximum stress for a simple beam can be reasonably approximated with the following equation (Note 13):

$$S = (3PL/2bd^2) \cdot [1 + 6(D/L)^2 - 4(d/L)(D/L)] \tag{6a}$$

where:
S, P, L, b, and d are the same as for Eq 5, and
D = deflection of the centerline of the specimen at the middle of the support span, mm (in.).

NOTE 13—When large support span-to-depth ratios are used, significant end forces are developed at the supports which affect the moment in a simply supported beam. An approximate correction factor is given in Eq 6a to correct for these end forces in large support span-to-depth ratio beams where relatively large deflections exist.

12.3 *Maximum Fiber Stress, Test Method II*—When a beam is loaded in flexure at two central points and supported at two outer points, the maximum stress in the outer fibers occurs between the two central loading points that define the load span (Fig. 2). This stress may be calculated for any point on the load-deflection curve for relatively small deflections by the following equation for a load span of one third of the support span (Note 14):

$$S = PL/bd^2 \tag{6b}$$

For a load span of one half of the support span:

$$S = 3PL/4bd^2 \tag{6c}$$

where:
S = stress in the outer fiber throughout the load span, MPa (psi),
P = load at a given point on the load-deflection curve, N (lbf),
L = support span, mm (in.),
b = width of beam, mm (in.), and
d = depth of beam, mm (in.).

NOTE 14—The limitations defined for Eq 5 in Notes 11 and 12 apply also to Eqs 6a, 6b, 6c, 6d, and 6e.

12.4 *Maximum Fiber Stress, Test Method II, for Beams Tested at Large Support Spans*—If support span-to-depth ratios greater than 16 to 1 are used with resultant deflections in excess of 10 % of the support span occurring, the maximum stress may be reasonably approximated with the following formula for a load span of one third of the support span:

$$S = (PL/bd^2) \cdot [1 + (4.70D^2/L^2) - (7.04Dd/L^2)] \tag{6d}$$

For a load span of one half of the support span:

$$S = (3PL/4bd^2) \cdot [1-(10.91Dd/L^2)] \tag{6e}$$

where:
S, P, L, b, and d are the same as for Eq 6b, and
D = maximum deflection of the center of the beam, mm (in.).

12.5 *Flexural Strength*—The flexural strength is equal to the maximum stress in the outer fibers at the moment of break (for highly orthotropic laminates, see Note 11). It is calculated in accordance with Eqs 5, 6a, 6b, 6c, 6d, and 6e by letting P equal the load at the moment of break. If the material does not break, this part of the test is not applicable. In this case, it is suggested that yield strength, if applicable, be calculated and that the corresponding strain be reported also (see 12.6, 12.8, and 12.9).

12.6 *Flexural Yield Strength*—Some materials that do not break at outer fiber strains up to 5 % may give load-deflection curves that show a point, Y, at which the load does not increase with an increase in deflection. In such cases, the flexural yield strength may be calculated in accordance with Eqs 5, 6a, 6b, or 6c by letting P equal the load at Point Y.

[6] For the theoretical details, see Whitney, J. M., Browning, C. E., and Mair, A., "Analysis of the Flexure Test for Laminated Composite Materials," *Composite Materials: Testing and Design (Third Conference), ASTM STP 546*, 1974, pp. 30–45.

12.7 *Flexural Offset Yield Strength*—Offset yield strength is the stress at which the stress-strain curve deviates by a given strain (offset) from the tangent to the initial straight line portion of the stress-strain curve. The value of the offset must be given whenever this property is calculated.

NOTE 15—This value may differ from flexural yield strength defined in 12.6. Both methods of calculation are described in the Annex to Test Method D 638.

12.8 *Stress at a Given Strain*—The maximum fiber stress at any given strain may be calculated in accordance with Eqs 5, 6a, 6b, 6c, 6d, and 6e by letting P equal the load read from the load-deflection curve at the deflection corresponding to the desired strain (for highly orthotropic laminates, see Note 11).

12.9 *Maximum Strain, Test Method I*—The maximum strain in the outer fibers also occurs at midspan, and it may be calculated as follows:

$$r = 6Dd/L^2 \tag{7}$$

where:

r = maximum strain in the outer fibers, mm/mm (in./in.),
D = maximum deflection of the center of the beam, mm (in.),
L = support span, mm (in.), and
d = depth, mm (in.).

12.10 *Maximum Strain, Test Method II*—The maximum strain in the outer fibers also occurs at midspan, and it may be calculated as follows for a load span of one third of the support span:

$$r = 4.70Dd/L^2 \tag{8a}$$

For load span of one half of the support span:

$$r = 4.36Dd/L^2 \tag{8b}$$

where D, d, L, and r are the same as for Eq 4a.

12.11 *Modulus of Elasticity*:

12.11.1 *Tangent Modulus of Elasticity, Test Method I*—The tangent modulus of elasticity, often called the "modulus of elasticity," is the ratio, within the elastic limit, of stress to corresponding strain and shall be expressed in megapascals (pounds per square inch). It is calculated by drawing a tangent to the steepest initial straight-line portion of the load-deflection curve and using Eq 9 (for highly anisotropic composites, see Note 16).

$$E_B = L^3 m/4bd^3 \tag{9}$$

where:

E_B = modulus of elasticity in bending, MPa (psi),
L = support span, mm (in.),
b = width of beam tested, mm (in.),
d = depth of beam tested, mm (in.), and
m = slope of the tangent to the initial straight-line portion of the load-deflection curve, N/mm (lbf/in.) of deflection.

NOTE 16—Shear deflections can seriously reduce the apparent modulus of highly anisotropic composites when they are tested at low span-to-depth ratios.[7] For this reason, a span-to-depth ratio of 60 to 1 is recommended for flexural modulus determinations. Flexural strength should be determined on a separate set of replicate specimens at a lower span-to-depth ratio that induces tensile failures in the outer fibers of the beam along its lower face. Since the flexural modulus of highly anisotropic laminates is a critical function of ply-stacking sequence, it will not necessarily correlate with tensile modulus, which is not stacking-sequence dependent.

12.11.2 *Tangent Modulus of Elasticity, Test Method II*—The tangent modulus of elasticity is the ratio, within the elastic limit, of stress to corresponding strain and shall be expressed in megapascals (pounds per square inch). It is calculated by drawing a tangent to the steepest initial straight-line portion of the load-deflection curve and using Eq 10a for a load span of one third the support span and Eq 10b for a load span of one half of the support span, as follows:

$$E_B = 0.21L^3 m/bd^3 \tag{10a}$$

$$E_B = 0.17L^3 m/bd^3 \tag{10b}$$

where E_B, m, L, b, and d are the same as for Eq 9 (for highly anisotropic composites, see Note 16).

12.11.3 *Secant Modulus of Elasticity*—The secant modulus of elasticity is the ratio of stress to corresponding strain at any given point on the stress-strain curve, or the slope of the straight line that joins the origin and a selected point on the actual stress-strain curve. It shall be expressed in megapascals (pounds per square inch). The selected point is generally chosen at a specified stress or strain. It is calculated in accordance with Eq 9 or 10a or 10b by letting m equal the slope of the secant to the load-deflection curve.

12.12 *Arithmetic Mean*—For each series of tests, the arithmetic mean of all values obtained shall be calculated to three significant figures and reported as the "average value" for the particular property in question.

12.13 *Standard Deviation*—The standard deviation (estimated) shall be calculated as follows and reported in two significant figures:

$$s = \sqrt{\frac{\Sigma X^2 - n\bar{X}^2}{n - 1}} \tag{11}$$

where:

s = estimated standard deviation,
X = value of single observation,
n = number of observations, and
$\bar{X}$ = arithmetic mean of the set of observations.

12.14 See Annex A1 for information on toe compensation.

13. Report

13.1 Report the following information:

13.1.1 Complete identification of the material tested, including type, source, manufacturer's code number, form, principal dimensions, and previous history (for laminated materials, ply-stacking sequence shall be reported).

13.1.2 Direction of cutting and loading specimens,

13.1.3 Conditioning procedure,

13.1.4 Depth and width of specimen,

13.1.5 Method used,

13.1.6 Procedure used,

13.1.7 Support span length,

13.1.8 Support span-to-depth ratio,

13.1.9 Radius of supports and loading noses,

[7] For a discussion of these effects, see Zweben, C., Smith, W. S., and Wardle, M. W., "Test Methods for Fiber Tensile Strength, Composite Flexural Modulus, and Properties of Fabric-Reinforced Laminates," *Composite Materials: Testing and Design (Fifth Conference)*, ASTM STP 674, 1979, pp. 228–262.

TABLE 4 Flexural Strength

NOTE 1—V_r is the within-laboratory coefficient of variation of the average and I_r = 2.83 V_r. (See 14.2.1 for application of I_r.)

NOTE 2—V_R is the total between-laboratory coefficient of variation of the average and I_R = 2.83 V_R. (See 14.2.2 for application of I_R.)

NOTE 3—Results in Table 4 are based on data collected using Method I only.

Material	Mean, 10^3 psi	Values as a Percent of the Mean			
		V_r	V_R	I_r	I_R
ABS	9.99	1.59	6.05	4.44	17.2
DAP thermoset	14.3	6.58	6.58	18.6	18.6
Cast acrylic	16.3	1.67	11.3	4.73	32.0
GR polyester	19.5	1.43	2.14	4.05	6.08
GR polycarbonate	21.0	5.16	6.05	14.6	17.1
SMC	26.0	4.76	7.19	13.5	20.4
	average (rMS)	4.08	7.08	11.5	20.0

TABLE 5 Flexural Modulus

NOTE 1—Results in Table 5 are based on data collected using Method I only.

Material	Mean, 10^3 psi	Values as a Percent of the Mean			
		V_r	V_R	I_r	I_R
ABS	338	4.79	7.69	13.6	21.8
Cast acrylic	485	2.89	7.18	8.15	20.4
GR polycarbonate	810	13.7	16.1	38.8	45.4
GR polyester	816	3.49	4.20	9.91	11.9
DAP thermoset	1790	5.52	5.52	15.6	15.6
SMC	1950	10.9	13.8	30.8	39.1
	average (rMS)	7.96	10.1	22.5	28.5

13.1.10 Rate of crosshead motion,

13.1.11 Maximum strain in the outer fibers of the specimen,

13.1.12 Flexural strength (if applicable), average value, and standard deviation,

13.1.13 Tangent or secant modulus of elasticity in bending, average value, standard deviation, and the strain level used if secant modulus,

13.1.14 Flexural yield strength (if desired), average value, and standard deviation,

13.1.15 Flexural offset yield strength (if desired), with offset or strain used, average value, and standard deviation,

13.1.16 Stress at any given strain up to and including 5 % (if desired), with strain used, average value, and standard deviation,

13.1.17 Type of behavior, whether yielding or rupture, or both, or other observation, occurring within the 5 % strain limit, and

13.1.18 Date of test.

14. Precision and Bias[8]

14.1 *Precision*—Tables 4 and 5 are based on round-robin tests conducted in 1984, involving six materials tested by six laboratories, using Method I. Each test result was the average of five individual determinations. Each laboratory obtained two test results for each material.

NOTE 17—**Caution**: The following explanations of r and R (14.2 through 14.2.3) are intended only to present a meaningful way of considering the approximate precision of these test methods. The data given in Tables 4 and 5 should not be applied rigorously to the acceptance or rejection of material, as those data are specific to the round robin and may not be representative of other lots, conditions, materials, or laboratories. Users of these test methods should apply the principles outlined in Practice E 691 to generate data specific to their laboratory and materials, or between specific laboratories. The principles of 14.2 through 14.2.3 would then be valid for such data.

14.2 For the materials indicated and for test results that are averages from testing five specimens, see Tables 4 and 5.

14.2.1 *Repeatability*—In comparing two test results for the same material, obtained by the same operator using the same equipment on the same day, those test results should be judged not equivalent if they differ by more than the I_r value for that material and condition.

14.2.2 *Reproducibility*—In comparing two test results for the same material, obtained by different operators using different equipment on different days, those test results should be judged not equivalent if they differ by more than the I_R value for that material and condition. (This applies between different laboratories or between different equipment within the same laboratory.)

14.2.3 The judgments in 14.2.1 and 14.2.2 will have an approximately 95 % (0.95) probability of being correct.

14.2.4 Other formulations may give somewhat different results.

14.3 For further information on the methodology used in this section, see Practice E 691.

14.4 *Bias*—No statement may be made about the bias of these test methods, as there is no standard reference material or reference test method that is applicable.

15. Keywords

15.1 flexural properties; plastics; stiffness; strength

[8] Supporting data are available from ASTM Headquarters. Request RR: D20-1128.

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